Compilers (Python)
CSCI P423/523, Fall 2022

Final

Name: ______________________

This exam has 12 questions, for a total of 100 points.

1. $\boxed{\text{5 points}}$ What is the observable behavior of the following $\mathcal{L}_{\mathsf{Fun}}$ program? (e.g. does it produce an error at compile time or runtime? does it produce an integer, which one? does it diverge?)

```
def f(x : Integer) -> tuple[int]
  v = (x, x)
  return v

v1 = f(3)
v2 = f(3)
v3 = v1
if v1 is v2:
  if v1 is v3:
    print(0)
  else:
    print(1)
else:
  if v1 is v3:
    print(2)
  else:
    print(3)
```

> **Solution:** This program outputs the number `2` because `v1 is v2` is false (they are tuples of different identity) and `v1 is v3` is true (they are aliases for the same tuple).

2. $\boxed{\text{5 points}}$ What is the observable behavior of the following $\mathcal{L}_{\mathsf{Tup}}$ program? (e.g. does it produce an error at compile time or runtime? does it produce an integer, which one? does it diverge?)

```
v1 = (3,3)
v2 = (3,3)
if v1[0] == v2[2]:
  print(0)
else:
  print(1)
```

> **Solution:** The program is not well-typed because the type of `v2` is `tuple[int,int]` but `v2[2]` tries to access its third element. So the type checker outputs and error.

3. $\boxed{\text{8 points}}$ Given the following $\mathcal{L}_{\mathsf{While}}$ program, apply the Explicate Control pass to translate it to $\mathcal{C}_{\mathsf{If}}$.

```
sum = 0
i = input_int()
while i > 0:
  sum = sum + i
  i = i - 1
tmp = 27 + sum
print(27 + sum)
```

Solution: (2 points per basic block)

```
start:
    sum = 0
    i = input_int()
    goto loop.35

loop.35:
    if i > 0:
      goto block.37
    else:
      goto block.36

block.37:
    sum = (sum + i)
    i = (i - 1)
    goto loop.35

block.36:
    tmp = 27 + sum
    print(tmp)
    return 0
```

4. 13 points Apply liveness analysis to the following pseudo-x86 program to determine the set of live locations before and after every instruction. (The callee and caller saved registers are listed in the Appendix of this exam.)

```
start:
    callq read_int
    movq %rax, x57
    movq $1, y58
    callq read_int
    movq %rax, i59
    jmp loop65

loop65:
    movq i59, tmp60
    cmpq $0, tmp60
    jg block67
    jmp block66

block66:
    movq y58, tmp64
    movq x57, %rax
    addq tmp64, %rax
    jmp conclusion

block67:
    movq y58, tmp61
    movq y58, tmp62
    movq tmp61, y58
    addq tmp62, y58
    movq i59, tmp63
    movq tmp63, i59
    subq $1, i59
    jmp loop65
```

Solution: (1/2 point per liveness set)

```
start:
   (set)
callq read_int
   (set)
movq %rax, x57
      { x57}
movq $1, y58
      { x57 y58}
callq read_int
      { x57 y58}
movq %rax, i59
      { x57 y58 i59}
jmp loop65
      { x57 y58 i59}

loop65:
      { x57 y58 i59}
movq i59, tmp60
      { x57 y58 i59 tmp60}
cmpq $0, tmp60
      { x57 y58 i59}
jg block67
      { x57 y58 i59}
jmp block66
      { x57 y58}
```

```
block66:
      { x57 y58}
movq y58, tmp64
      { tmp64 x57}
movq x57, %rax
      { tmp64}
addq tmp64, %rax
      {}
jmp conclusion
      {}

block67:
      { x57 y58 i59}
movq y58, tmp61
      { tmp61 x57 y58 i59}
movq y58, tmp62
      { tmp61 tmp62 x57 i59}
movq tmp61, y58
      { tmp62 x57 y58 i59}
addq tmp62, y58
      { x57 y58 i59}
movq i59, tmp63
      { tmp63 x57 y58}
movq tmp63, i59
      { x57 y58 i59}
subq $1, i59
      { x57 y58 i59}
jmp loop65
      { x57 y58 i59}
```

5. 10 points Fill in the blanks for the following `expose_alloc_tuple` auxilliary function of the Expose Allocation pass that translates from $\mathcal{L}_{\mathsf{Tup}}$ to $\mathcal{L}_{\mathsf{Alloc}}$. (The grammar for $\mathcal{L}_{\mathsf{Alloc}}$ is in the Appendix.)

```
def expose_alloc_tuple(es, tupleType, allocExp):
    n = len(es)
    num_bytes = ___(a)___
    vec = generate_name('alloc')
    space_left = Compare(___(b)___, [Lt()],
                         [GlobalValue('fromspace_end')])
    xs = [Name(generate_name('init')) for e in es]
    inits = [Assign([x], e) for (x,e) in zip(xs,es)]
    initVec = []
    i = 0
    for x in xs:
        initVec += [___(c)___]
        i += 1
    return Begin(inits \
             + [If(space_left, [], [___(d)___])] \
             + [Assign([Name(vec)], allocExp)] \
             + initVec,
             Name(vec))

def expose_alloc_exp(e: expr) -> expr:
    match e:
        case Tuple(es, Load()):
            alloc = Allocate(len(es), e.has_type)
            return expose_alloc_tuple(___(e)___, e.has_type, alloc)
        ...
```

Solution: (2 points each)

```
(a) (n + 1) * 8
(b) BinOp(GlobalValue('free_ptr'), Add(), Constant(num_bytes))
(c) Assign([Subscript(Name(vec), Constant(i),Store())], x)
(d) Collect(num_bytes)
(e) [expose_alloc_exp(e) for e in es]
```

6. 4 points In the `expose_alloc_tuple` function of the previous question, why are the intializing expressions `es` assigned to the temporary variables `xs` instead of using them directly in the tuple initialization?

Solution: The reason is that between the allocation of the tuple and the initialization of its elements, we cannot allow a call to `collect` because then the garbage collector would try to traverse a partially-initialized tuple, causing it to potentially jump to random locations in memory. The initializing expressions may contain tuple-creation expressions and hence calls to `collect`. The `let` binding of the intializing expressions causes them to be executed first, prior to the allocation and initialization of the tuple.

7. 6 points Describe the layout of the 64-bit tag at the beginning of every tuple.

Solution:

- Bit position 0 is set to 0 when the tuple has been copied into the TO space (in the process of doing a copy collection) and it is set to 1 otherwise. If it is set to 0, then the 64 bits are the address of the new location in the TO space. **(2 points)**
- Bit position 1 through 6 stores the length of the tuple. **(2 points)**
- Bit position 7 through 57 is the pointer mask. It says, for each element of the tuple, whether the element is a pointer (that is, a tuple) or something else (like an integer or Boolean). **(2 points)**

8. [10 points] Fill in the blanks for the following `explicate_control` that translates $\mathcal{L}^{mon}_{\mathsf{FunRef}}$ programs into $\mathcal{C}_{\mathsf{Fun}}$ programs.

```
def explicate_tail(e : expr, blocks: Dict[str, List[stmt]]) -> List[stmt]:
    match e:
        case Call(Name(f), args) if f in builtin_functions:
          return [___(a)___]
        case Call(func, args):
          return [___(b)___]
        ...

def explicate_pred(cnd: expr, thn: List[stmt], els: List[stmt],
                   basic_blocks: Dict[str, List[stmt]]) -> List[stmt]:
    match cnd:
        case Call(func, args):
            tmp = generate_name('call')
            return [___(c)___,
                    If(Compare(Name(tmp), [Eq()], [Constant(False)]),
                       create_block(els, basic_blocks),
                       create_block(thn, basic_blocks))]

        ...

def explicate_stmt(s: stmt, cont: List[stmt],
                   blocks: Dict[str, List[stmt]]) -> List[stmt]:
    match s:
        case Return(value):
            return ___(d)___
        ...

def explicate_def(d) -> stmt:
    match d:
        case FunctionDef(name, params, body, _, returns, _):
            new_body = []
            blocks = {}
            if isinstance(returns, VoidType):
                body = body + [Return(Constant(None))]
            for s in reversed(body):
                new_body = ___(e)___
            blocks[label_name(name + '_start')] = new_body
            return FunctionDef(name, params, blocks, None, returns, None)
        ...
```

Solution: (2 points each)

```
(a) Return(e)
(b) TailCall(func, args)
(c) Assign([Name(tmp)], cnd)
(d) explicate_tail(value, blocks)
(e) explicate_stmt(s, new_body, blocks)
```

9. 6 points What is the purpose of the Reveal Functions pass? How does the output of Reveal Functions facilitate decisions made in later passes of the compiler?

Solution: The Reveal Functions pass separates the references to global functions from references to local variables, changing the former to `FunRef`. **(2 points)** The later passes can then treat them differently, in particular,

- In Remove Complex Operands, `FunRef` is treated as a complex operand to make sure it only appears on the righ-hand side of an assignment statement. **(2 points)**
- In Instruction Selection, each assignment with `FunRef` on the right-hand side is translated to a `leaq` instruction that obtains the function's address from the function's label. **(2 points)**

10. 8 points Describe the general layout of the procedure call frame that your compiler uses.

Solution: The procedure call frame stores the following information:

- The return address, i.e., the address of the caller. **(2 points)**
- The caller's value for `rbp`. **(2 points)**
- The caller's values of the callee-saved registers that are going to be used in this function. **(2 points)**
- The spilled local variables. **(2 points)**

11. 13 points Apply Instruction Selection to the following two functions, translating them from $\mathcal{C}_{\mathsf{Fun}}$ to $\text{x86}^{\mathsf{Def}}_{\mathsf{callq*}}$. (The definitions of $\mathcal{C}_{\mathsf{Fun}}$ and $\text{x86}^{\mathsf{Def}}_{\mathsf{callq*}}$ are in the Appendix, as is the list of argument-passing registers.) (The function `even` calls `odd`, but you do not need to translate the `odd` function for this exam question, so its definition is omitted.) (The below functions are presented in concrete syntax except for the `FunRef` nodes.)

```
def even(x : int) -> bool:
  even_start:
        if x == 0:
          goto block.146
        else:
          goto block.147
  block.146:
        return True
  block.147:
        fun.138 = FunRef(odd, 1)
        tmp.139 = (x - 1)
        tail fun.138(tmp.139)

def main() -> int:
  main_start:
        fun.142 = FunRef(even, 1)
        tmp.143 = input_int()
        call.152 = fun.142(tmp.143)
        if call.152 == False:
          goto block.153
        else:
          goto block.154
  block.153:
        tmp.144 = 0
        goto block.151
  block.154:
        tmp.144 = 42
        goto block.151
  block.151:
        print(tmp.144)
        return 0
```

Solution: (approx. 1/2 point per instruction)

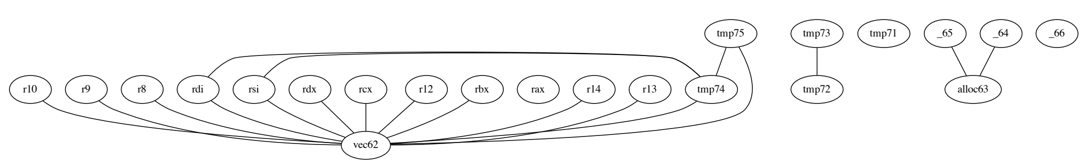
```
def even() -> bool:
  even_start:
        movq %rdi, x
        cmpq $0, x
        je block.146
        jmp block.147
  block.146:
        movq $1, %rax
        jmp even_conclusion
  block.147:
        leaq odd(%rip), fun.138
        movq x, tmp.139
```

```
        subq $1, tmp.139
        movq tmp.139, %rdi
        tailjmp fun.138

def main() -> int:
  main_start:
        leaq even(%rip), fun.142
        callq read_int
        movq %rax, tmp.143
        movq tmp.143, %rdi
        callq* fun.142
        movq %rax, call.152
        cmpq $0, call.152
        je block.153
        jmp block.154
  block.151:
        movq tmp.144, %rdi
        callq print_int
        movq $0, %rax
        jmp main_conclusion
  block.153:
        movq $0, tmp.144
        jmp block.151
  block.154:
        movq $42, tmp.144
        jmp block.151
```

12. 12 points Draw the interference graph for the following program fragment by adding edges between the nodes below. You do not need to include edges between two registers. The live-after set for each instruction is given to the right of each instruction and the types of each variable is listed below. (The callee and caller saved registers are listed in the Appendix of this exam.)

```
def main() -> int:
  var_types:
    tmp73 : int, tmp72 : int, tmp75 : Callable[[int], int],
    tmp74 : Callable[Callable[[int], int], tuple[int, int]], Void), tmp71 : int,
    _65 : int, _64 : int, _66 : int, alloc63 : tuple[int, int],
    vec62 : tuple[int,int]

mainstart:
    {}
movq free_ptr(%rip), tmp71
    {tmp71}
movq tmp71, tmp72
    {tmp72}
addq $24, tmp72
    {tmp72}
movq fromspace_end(%rip), tmp73
    {tmp72 tmp73}
cmpq tmp73, tmp72
    {}
jl block77
    {}
jmp block78
    {}

block77:
     {}
movq $0, _66
    {}
jmp block76
    {}

block78:
    {}
movq %r15, %rdi
    {rdi}
movq $24, %rsi
    {rdi rsi}
callq collect
    {}
jmp block76
    {}

block76:
    {}
movq free_ptr(%rip), %r11
    {}
addq $24, free_ptr(%rip)
    {}
movq $5, 0(%r11)
    {r11}
movq %r11, alloc63
    {alloc63}
movq alloc63, %r11
    {alloc63}
movq $0, 8(%r11)
    {alloc63}
movq $0, _65
    {alloc63}
movq alloc63, %r11
    {alloc63}
movq $41, 16(%r11)
    {alloc63}
movq $0, _64
    {alloc63}
movq alloc63, vec62
    {vec62}
leaq map_vec_57(%rip), tmp74
    {vec62 tmp74}
leaq add158(%rip), tmp75
    {vec62 tmp74 tmp75}
movq tmp75, %rdi
    {tmp74 rdi vec62}
movq vec62, %rsi
    {rsi tmp74 rdi vec62}
callq *tmp74
    {vec62}
movq vec62, %r11
    {r11}
movq 16(%r11), %rax
    {rax}
jmp mainconclusion
    {rax}
)
```

Solution:



Appendix

The caller-saved registers are:

```
rax rcx rdx rsi rdi r8 r9 r10 r11
```

and the callee-saved registers are:

```
rsp rbp rbx r12 r13 r14 r15
```

The argument-passing registers are:

```
rdi rsi rdx rcx r8 r9
```

Grammar for $\mathcal{L}_{\mathsf{While}}$

$$
\begin{array}{rcl}
\mathit{exp} & ::= & \texttt{Constant(}\mathit{int}\texttt{)} \mid \texttt{Call(Name('input\_int'),[])} \\
& \mid & \texttt{UnaryOp(USub(),}\mathit{exp}\texttt{)} \mid \texttt{BinOp(}\mathit{exp}\texttt{,Add(),}\mathit{exp}\texttt{)} \\
& \mid & \texttt{BinOp(}\mathit{exp}\texttt{,Sub(),}\mathit{exp}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{Expr(Call(Name('print'),[}\mathit{exp}\texttt{]))} \mid \texttt{Expr(}\mathit{exp}\texttt{)} \\
\hline
\mathit{exp} & ::= & \texttt{Name(}\mathit{var}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{Assign([Name(}\mathit{var}\texttt{)], }\mathit{exp}\texttt{)} \\
\hline
\mathit{boolop} & ::= & \texttt{And()} \mid \texttt{Or()} \\
\mathit{unaryop} & ::= & \texttt{Not()} \\
\mathit{cmp} & ::= & \texttt{Eq()} \mid \texttt{NotEq()} \mid \texttt{Lt()} \mid \texttt{LtE()} \mid \texttt{Gt()} \mid \texttt{GtE()} \\
\mathit{bool} & ::= & \texttt{True} \mid \texttt{False} \\
\mathit{exp} & ::= & \texttt{Constant(}\mathit{bool}\texttt{)} \mid \texttt{BoolOp(}\mathit{boolop}\texttt{,[}\mathit{exp}\texttt{,}\mathit{exp}\texttt{])} \\
& \mid & \texttt{Compare(}\mathit{exp}\texttt{,[}\mathit{cmp}\texttt{],[}\mathit{exp}\texttt{])} \mid \texttt{IfExp(}\mathit{exp}\texttt{,}\mathit{exp}\texttt{,}\mathit{exp}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{If(}\mathit{exp}\texttt{, }\mathit{stmt}^{+}\texttt{, }\mathit{stmt}^{+}\texttt{)} \\
\hline
\mathit{stmt} & ::= & \texttt{While(}\mathit{exp}\texttt{, }\mathit{stmt}^{+}\texttt{, [])} \\
\mathcal{L}_{\mathsf{While}} & ::= & \texttt{Module(}\mathit{stmt}^{*}\texttt{)}
\end{array}
$$

Grammar for $\mathcal{C}_{\mathsf{If}}$

$$
\begin{array}{rcl}
\mathit{atm} & ::= & \texttt{Constant(}\mathit{int}\texttt{)} \mid \texttt{Name(}\mathit{var}\texttt{)} \mid \texttt{Constant(}\mathit{bool}\texttt{)} \\
\mathit{exp} & ::= & \mathit{atm} \mid \texttt{Call(Name('input\_int'),[])} \mid \texttt{UnaryOp(USub(),}\mathit{atm}\texttt{)} \\
& \mid & \texttt{BinOp(}\mathit{atm}\texttt{,Sub(),}\mathit{atm}\texttt{)} \mid \texttt{BinOp(}\mathit{atm}\texttt{,Add(),}\mathit{atm}\texttt{)} \\
& \mid & \texttt{Compare(}\mathit{atm}\texttt{,[}\mathit{cmp}\texttt{],[}\mathit{atm}\texttt{])} \\
\mathit{stmt} & ::= & \texttt{Expr(Call(Name('print'),[}\mathit{atm}\texttt{]))} \mid \texttt{Expr(}\mathit{exp}\texttt{)} \\
& \mid & \texttt{Assign([Name(}\mathit{var}\texttt{)], }\mathit{exp}\texttt{)} \\
\mathit{tail} & ::= & \texttt{Return(}\mathit{exp}\texttt{)} \mid \texttt{Goto(}\mathit{label}\texttt{)} \\
& \mid & \texttt{If(Compare(}\mathit{atm}\texttt{,[}\mathit{cmp}\texttt{],[}\mathit{atm}\texttt{]), [Goto(}\mathit{label}\texttt{)], [Goto(}\mathit{label}\texttt{)])} \\
\mathcal{C}_{\mathsf{If}} & ::= & \texttt{CProgram(}\{\mathit{label}\texttt{: [}\mathit{stmt},\ldots,\mathit{tail}\texttt{]},\ldots\}\texttt{)}
\end{array}
$$

Grammar for $\mathcal{L}_{\mathsf{Tup}}$

$$
\begin{array}{rcl}
\mathit{exp} & ::= & \texttt{Constant(}\mathit{int}\texttt{)} \mid \texttt{Call(Name('input\_int'),[])} \\
& \mid & \texttt{UnaryOp(USub(),}\mathit{exp}\texttt{)} \mid \texttt{BinOp(}\mathit{exp}\texttt{,Add(),}\mathit{exp}\texttt{)} \\
& \mid & \texttt{BinOp(}\mathit{exp}\texttt{,Sub(),}\mathit{exp}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{Expr(Call(Name('print'),[}\mathit{exp}\texttt{]))} \mid \texttt{Expr(}\mathit{exp}\texttt{)} \\
\hline
\mathit{exp} & ::= & \texttt{Name(}\mathit{var}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{Assign([Name(}\mathit{var}\texttt{)], }\mathit{exp}\texttt{)} \\
\hline
\mathit{boolop} & ::= & \texttt{And()} \mid \texttt{Or()} \\
\mathit{unaryop} & ::= & \texttt{Not()} \\
\mathit{cmp} & ::= & \texttt{Eq()} \mid \texttt{NotEq()} \mid \texttt{Lt()} \mid \texttt{LtE()} \mid \texttt{Gt()} \mid \texttt{GtE()} \\
\mathit{bool} & ::= & \texttt{True} \mid \texttt{False} \\
\mathit{exp} & ::= & \texttt{Constant(}\mathit{bool}\texttt{)} \mid \texttt{BoolOp(}\mathit{boolop}\texttt{,[}\mathit{exp}\texttt{,}\mathit{exp}\texttt{])} \\
& \mid & \texttt{Compare(}\mathit{exp}\texttt{,[}\mathit{cmp}\texttt{],[}\mathit{exp}\texttt{])} \mid \texttt{IfExp(}\mathit{exp}\texttt{,}\mathit{exp}\texttt{,}\mathit{exp}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{If(}\mathit{exp}\texttt{, }\mathit{stmt}^{+}\texttt{, }\mathit{stmt}^{+}\texttt{)} \\
\hline
\mathit{stmt} & ::= & \texttt{While(}\mathit{exp}\texttt{, }\mathit{stmt}^{+}\texttt{, [])} \\
\hline
\mathit{cmp} & ::= & \texttt{Is()} \\
\mathit{exp} & ::= & \texttt{Tuple(}\mathit{exp}^{+}\texttt{,Load())} \mid \texttt{Subscript(}\mathit{exp}\texttt{,Constant(}\mathit{int}\texttt{),Load())} \\
& \mid & \texttt{Call(Name('len'),[}\mathit{exp}\texttt{])} \\
\mathcal{L}_{\mathsf{Tup}} & ::= & \texttt{Module(}\mathit{stmt}^{*}\texttt{)}
\end{array}
$$

Grammar for $\mathcal{L}_{\mathsf{Alloc}}$

The $\mathcal{L}_{\mathsf{Alloc}}$ language extends $\mathcal{L}_{\mathsf{Tup}}$ with the following grammar rules:

$$
\begin{array}{rcl}
\mathit{exp} & ::= & \texttt{Collect(}\mathit{int}\texttt{)} \mid \texttt{Allocate(}\mathit{int}, \mathit{type}\texttt{)} \mid \texttt{GlobalValue(}\mathit{name}\texttt{)} \\
\mathit{stmt} & ::= & \texttt{Assign([Subscript(}\mathit{exp}\texttt{,}\mathit{int}\texttt{,Store())], }\mathit{exp}\texttt{)}
\end{array}
$$

Grammar for $\mathcal{L}_{\mathsf{Fun}}$

exp	::=	`Constant(`*int*`)` | `Call(Name('input_int'),[])`
	|	`UnaryOp(USub(),`*exp*`)` | `BinOp(`*exp*`,Add(),`*exp*`)`
	|	`BinOp(`*exp*`,Sub(),`*exp*`)`
stmt	::=	`Expr(Call(Name('print'),[`*exp*`]))` | `Expr(`*exp*`)`
exp	::=	`Name(`*var*`)`
stmt	::=	`Assign([Name(`*var*`)], `*exp*`)`
boolop	::=	`And()` | `Or()`
unaryop	::=	`Not()`
cmp	::=	`Eq()` | `NotEq()` | `Lt()` | `LtE()` | `Gt()` | `GtE()`
bool	::=	`True` | `False`
exp	::=	`Constant(`*bool*`)` | `BoolOp(`*boolop*`,[`*exp*`,`*exp*`])`
	|	`Compare(`*exp*`,[`*cmp*`],[`*exp*`])` | `IfExp(`*exp*`,`*exp*`,`*exp*`)`
stmt	::=	`If(`*exp*`, `$stmt^+$`, `$stmt^+$`)`
stmt	::=	`While(`*exp*`, `$stmt^+$`, [])`
cmp	::=	`Is()`
exp	::=	`Tuple(`exp^+`,Load())` | `Subscript(`*exp*`,Constant(`*int*`),Load())`
	|	`Call(Name('len'),[`*exp*`])`
type	::=	`IntType()` | `BoolType()` | `VoidType()` | `TupleType[`$type^+$`]`
	|	`FunctionType(`$type^*$`, `*type*`)`
exp	::=	`Call(`*exp*`, `exp^*`)`
stmt	::=	`Return(`*exp*`)`
params	::=	`(`*var*`,`*type*`)`*
def	::=	`FunctionDef(`*var*`, `*params*`, `$stmt^+$`, None, `*type*`, None)`
$\mathcal{L}_{\mathsf{Fun}}$	::=	`Module([`*def* … *stmt* …`])`

Grammar for $\mathcal{L}^{mon}_{\mathsf{FunRef}}$

```
atm    ::= Constant(int) | Name(var)
exp    ::= atm | Call(Name('input_int'),[])
        |  UnaryOp(USub(),atm) | BinOp(atm,Add(),atm)
        |  BinOp(atm,Sub(),atm)
stmt   ::= Expr(Call(Name('print'),[atm])) | Expr(exp)
        |  Assign([Name(var)], exp)
----------------------------------------------------------------
atm    ::= Constant(bool)
exp    ::= Compare(atm,[cmp],[atm]) | IfExp(exp,exp,exp)
        |  Begin(stmt*, exp)
stmt   ::= If(exp, stmt*, stmt*)
----------------------------------------------------------------
stmt   ::= While(exp, stmt+, [])
----------------------------------------------------------------
exp    ::= Subscript(atm,atm,Load())
        |  Call(Name('len'),[atm])
        |  Allocate(int, type) | GlobalValue(var)
stmt   ::= Assign([Subscript(atm,atm,Store())], atm)
        |  Collect(int)
----------------------------------------------------------------
type     ::= IntType() | BoolType() | VoidType() | TupleType[type+]
          |  FunctionType(type*, type)
exp      ::= FunRef(label, int) | Call(atm, atm*)
stmt     ::= Return(exp)
params   ::= (var,type)*
def      ::= FunctionDef(var, params, stmt+, None, type, None)
L^mon_FunRef ::= Module([def ... stmt ...])
```

Grammar for $\mathcal{C}_{\mathsf{Fun}}$

```
atm    ::= Constant(int) | Name(var) | Constant(bool)
exp    ::= atm | Call(Name('input_int'),[]) | UnaryOp(USub(),atm)
        |  BinOp(atm,Sub(),atm) | BinOp(atm,Add(),atm)
        |  Compare(atm,[cmp],[atm])
stmt   ::= Expr(Call(Name('print'),[atm])) | Expr(exp)
        |  Assign([Name(var)], exp)
tail   ::= Return(exp) | Goto(label)
        |  If(Compare(atm,[cmp],[atm]), [Goto(label)], [Goto(label)])
----------------------------------------------------------------
exp    ::= Subscript(atm,atm,Load()) | Allocate(int, type)
        |  GlobalValue(var) | Call(Name('len'),[atm])
stmt   ::= Collect(int)
        |  Assign([Subscript(atm,atm,Store())], atm)
----------------------------------------------------------------
exp      ::= FunRef(label, int) | Call(atm, atm*)
tail     ::= TailCall(atm, atm*)
params   ::= [(var,type), ...]
block    ::= label:stmt* tail
blocks   ::= {block, ...}
def      ::= FunctionDef(label, params, blocks, None, type, None)
C_Fun    ::= CProgramDefs([def, ...])
```

Grammar for $\text{x86}^{\mathsf{Def}}_{\mathsf{callq*}}$

$$
\begin{array}{lcl}
\mathit{arg} & ::= & \texttt{Constant(}\mathit{int}\texttt{)} \mid \texttt{Reg(}\mathit{reg}\texttt{)} \mid \texttt{Deref(}\mathit{reg}\texttt{,}\mathit{int}\texttt{)} \mid \texttt{ByteReg(}\mathit{reg}\texttt{)} \\
 & \mid & \texttt{Global(}\mathit{label}\texttt{)} \mid \texttt{FunRef(}\mathit{label}\texttt{, }\mathit{int}\texttt{)} \\
\mathit{instr} & ::= & \ldots \mid \texttt{IndirectCallq(}\mathit{arg}\texttt{, }\mathit{int}\texttt{)} \mid \texttt{TailJmp(}\mathit{arg}\texttt{, }\mathit{int}\texttt{)} \\
 & \mid & \texttt{Instr('leaq',[}\mathit{arg}\texttt{,Reg(}\mathit{reg}\texttt{)])} \\
\mathit{block} & ::= & \mathit{label}\texttt{:}\, \mathit{instr}^{*} \\
\mathit{blocks} & ::= & \{\mathit{block}\texttt{,} \ldots\} \\
\mathit{def} & ::= & \texttt{FunctionDef(}\mathit{label}\texttt{, [], }\mathit{blocks}\texttt{, \_, }\mathit{type}\texttt{, \_)} \\
\text{x86}^{\mathsf{Def}}_{\mathsf{callq*}} & ::= & \texttt{X86ProgramDefs([}\mathit{def}\texttt{,}\ldots\texttt{])}
\end{array}
$$